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Risks, Designs, and Research for Fire Safety in Spacecraft

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SUMMARY

Current fire protection for spacecraft relies mainly on fire prevention through the use of nonflammable materials and strict storage controls of other materials. The Shuttle also has smoke detectors and fire extinguishers, using technology similar to aircraft practices. While experience has shown that the current fire protection is adequate, future improvements in fire-safety technology to meet the challenges of long-duration space missions, such as the Space Station *Freedom*, are essential. The designs of *Freedom* include photoelectric smoke detectors, multi-band flame detectors, and carbon dioxide extinguishers. All spacecraft fire-protection systems, however, must deal with the unusual combustion characteristics and operational problems in the low-gravity environment. The paper discusses the features of low-gravity combustion that affect spacecraft fire safety, and the issues in fire protection for *Freedom* that must be addressed eventually to provide effective and conservative fire-protection systems.

INTRODUCTION

This paper is a review of low-gravity combustion knowledge and its application to fire protection in human-crew spacecraft. The techniques for spacecraft fire safety originated from those of aircraft, but spacecraft protection must respond to the unusual aspects of fires in the space environment (refs. 1 and 2). An orbiting spacecraft experiences a balance of forces that reduces the net gravitational attraction to near-zero, greatly reducing buoyant flows and profoundly influencing the characteristics of fires. Many problems are yet to be defined, let alone solved, in the application of low-gravity combustion science toward practical techniques in fire safety (ref. 3).

Fires can occur in space. There have been three minor incidents, involving electrical shorts and component overheating, in Shuttle missions to date. These occurrences caused only trivial damage to the materials involved, but the incidents were examples of possible fire scenarios that could have harmful consequences if not properly anticipated and promptly treated (ref. 4).

The current U.S. space transportation system, the Shuttle, is a closed environment susceptible to the risk of fire damage and injury. Shuttle fire-safety procedures incorporate provisions for prevention, detection, and suppression. Since the missions of the Shuttle are relatively short, the vehicle can return to Earth promptly for clean-up and repair after a fire. In the future, however, missions will be extended. The major thrust will be in the development of the Space Station *Freedom*, a permanently orbiting habitat, laboratory, and workshop. *Freedom* will be a complex structure, designed for a variety of housekeeping, scientific, and commercial enterprises that may increase the probability of fire incidents. Fire and post-fire protection must depend on provisions carried onboard *Freedom*, since external rescue opportunities can be many days away.

This paper is based on a previous review of spacecraft risk analyses prepared by the authors (ref. 5). The scope of the paper covers a discussion of spacecraft fire-safety strategies, some features of low-gravity fires that influence safety, current approaches and proposed designs for U.S. spacecraft, problems in fire protection, and suggested research to address these problems.

SPACECRAFT FIRE-SAFETY RISKS AND STRATEGIES

The confined quarters, limited fire-fighting resources, lack of external rescue capability, and the poorly understood effects of the microgravity environment in spacecraft make the consequences of fire incidents very dangerous. Nevertheless, experience has shown that the Shuttle fire protection is effective in responding to and limiting fire incidents. For the fire protection of the future Space Station *Freedom*, however, there are strong incentives to improve procedures and institute quantitative risk assessments. Practices acceptable for the short missions of the Shuttle may not be adequate for the Space Station *Freedom*, because of increased fire risks in the scientific, workshop, and daily living (cooking, laundry, trash disposal, for example) operations. For *Freedom*, there will be limited rescue options, and fire protection, controls, and repairs must be performed in orbit using supplies on hand. Because of the long-duration mission assignments, there is also the possibility of relaxation of crew discipline and alertness to danger.

Early in the definition phase of the *Freedom* program, Rockwell International investigators evaluated a number of safety concepts (refs. 6 and 7). The elements of the U.S. space program fire-safety strategy, as derived by the authors (ref. 5) from this early assessment, is illustrated in figure 1. The strategy is, in effect, a tradeoff of minimum risk levels against practical fire protection. The desired, lowest-risk element is fire prevention through exclusion (or minimization) of fire-causing factors, primarily by the removal or reduction of potential flammable materials. Since the success of this approach cannot be guaranteed, the strategy must recognize the finite probability of the initiation of a fire (or overheating or smoldering). The higher-risk response to the incipient fire is through detection. If detection is timely, the incipient fire may be alleviated by a minimal response (turning off power, for example). If necessary, timely detection will need to be supplemented by the higher-risk element of extinguishment. Finally, an important concern in spacecraft fire safety is on-board recovery, the operations of environmental alleviation and post-fire repairs. A delay or failure of detection or extinguishment leads to unacceptable risks. The U.S. space program safety philosophy defines "unacceptable" risks as those exceeding the worst-case option of a fire that will cause no crew injuries but possible component damages suspending some operations temporarily (ref. 6).

As the designs of *Freedom* evolved, specific risk models have been proposed. Kaplan (ref. 8) developed qualitative fault trees to define the alternative paths from initiating fire events that threaten the unacceptable aftermaths of heat, toxic gases, and structural failure to the acceptable results of safe conditions, crew rescue, or crew endangerment, stated in the order of increasing risk. Another quantitative risk-assessment proposal of Apostolakis (ref. 9) requires three evaluations:

(1) The identification of fire scenarios and critical locations,
(2) The estimation of fire growth times, and
(3) The estimation of response times (fire detection and suppression, for example).

All of these risk analyses recognize the strong influence of the low-gravity space environment on fire characteristics. None of them can offer, however, specific strategies designed to address the unique hazards of fires in space; nor can they anticipate the new safety challenges arising in the evolving designs and assembly procedures for *Freedom.*

MICROGRAVITY COMBUSTION SCIENCE

The Space Environment

Typical fires have large density gradients created by the rapid heat release in flames (temperature increases can approach 1000 K/mm, for example). Under the influence of gravity, these density gradients cause substantial natural convection or buoyancy-driven upward flows. The placement of fire detectors on ceilings, for example, anticipates the predictable upward bulk motion of combustion products in normal gravity. Orbiting space vehicles, however, are in a state of near-equilibrium between centrifugal and gravitational forces. Thus small, unattached objects within the spacecraft experience near-zero accelerations, ranging from about 10^{-7} to about 10^{-4} times normal Earth gravity levels (1 g, or 9.8 m/s^2). In this "microgravity" environment, even very large temperature gradients result in greatly reduced buoyancy forces, although buoyant motion may not be entirely negligible. Under these circumstances, other flow-field components may emerge to influence flame spreading and flammability, including low-level forced flows such as cabin-air ventilation.

Microgravity Combustion Research

Originally, microgravity combustion research focused upon tests of classical combustion problems formulated theoretically but omitting the gravitational effects of buoyant fluid motion. Current research in microgravity combustion is more comprehensive, and it seeks analytical and experimental solutions to three overlapping sets of problems. These are:

(1) The basic understanding of combustion processes simplified by the absence (or near absence) of buoyant convection,

(2) The improved understanding of certain physical mechanisms in flames, for example, mass diffusion, radiation heat transfer, or surface-tension driven convection, ordinarily overwhelmed by buoyant convection processes, and

(3) The practical determination of the limitations of flammability, flame stabilization, and flame spreading in the low-gravity environment (ref. 10).

Microgravity combustion research spans an interesting variety of flame types. Studies of stabilized and freely propagating laminar flames in premixed gases contribute important information on flammability limits (ref. 11). Other studies on jet diffusion flames (ref. 12), flames spreading over liquid pools (ref. 13), and flames on thin solid fuels (ref. 14) contribute to the knowledge of flame spreading, soot formation, and radiant emissions in these practical fire environments. The microgravity environment is also utilized to isolate and stabilize single fuel droplets and particle suspensions for basic combustion studies in these important two-phase systems (ref. 10).

Experimental efforts in microgravity combustion have been active since appropriate testing facilities became available in the 1960's. Orbiting spacecraft would provide the ideal laboratory or demonstration facility for these experiments. Until recently, however, there was only one combustion-related study in space, a set of experiments conducted in the 1974 Skylab orbiting laboratory (ref. 15). In October 1990, however, a new Shuttle experiment program on paper-fuel flammability in low gravity (the Solid Surface Combustion Experiment, ref. 16) was initiated. To date, three tests under differing atmospheric pressures have been conducted, each in separate Shuttle missions. Data and analyses from these tests will be available soon.

Thus, almost all reduced-gravity combustion research has been conducted in two types of ground-based free-fall facilities that offer low-gravity conditions for limited time periods (ref. 17). These facilities are drop towers, which can provide 2 to 5 sec of $\sim 10^{-6}$ g (fig. 2), and aircraft flying parabolic trajectories, which can provide about 20 sec of $\sim 10^{-2}$ g (fig. 3). The ability to perform useful low-gravity research in these ground-based facilities has proved to be extremely valuable to the understanding of low-gravity fire science. Results of ground-based tests, for example, are essential in establishing the combustion models for the interpretations of the data from the on-going Shuttle Solid Surface Combustion Experiment (ref. 18).

SPACECRAFT DESIGNS FOR FIRE SAFETY

Fire Prevention

In human-crew spacecraft, oxygen must be present in the atmosphere for life support. While good design and housekeeping practices minimize ignition sources through electrical-circuit protection and grounding, for example, ignition sources are always assumed to be present. Therefore, with reference to the familiar fire "triangle" of fuel, ignition, and oxygen, the focus of spacecraft fire prevention is on the exclusion, or, in practice the reduction, of potential fuels.

Current practices in material controls.— Materials used in habitable volumes of spacecraft must be evaluated to meet prescribed criteria of flammability. NASA specifications (ref. 19) require the flammability tests, NHB 8060.1C Upward Flame Propagation (Test 1) for materials in the form of sheets, foams, and coatings, and NHB 8060.1C Electrical Wire Insulation Flammability (Test 4) for insulation materials for electrical wiring. The tests are conducted in an apparatus (shown in fig. 4 for Test 1) contained within a sealed chamber under a worst-case flammable atmosphere (air enriched to 30 vol % O_2 for most Shuttle applications) and with upward flame propagation to aid flame spread by the direction of buoyancy. After exposure to a promoted ignition source for 25 s, a material is considered self-extinguishing if it either fails to propagate a flame away from the igniter or burns for a distance less than 15 cm, without any transfer of burning debris to ignite the paper sheet mounted below the specimen (fig. 4).

There are several supplemental spacecraft flammability tests. NHB 8060.1C Heat and Visible Smoke Release Rates (Test 2) is an application of the ASTM E 1354-90 Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter. Test 2 is required to evaluate materials with exposed surface areas greater than 0.37 m^2, and it may be used for supplementary data on the flammability of materials that fail to meet the requirements of Test 1. For volatile liquids, NHB 8060.1C Flash Point of Liquids (Test 3) is equivalent to the ASTM D 93-85 Test Methods for Flash Point by the Pensky-Martens Closed Tester. NHB 8060.1C Flammability Test for Materials in Vented or

Sealed Containers (Test 8) assesses the storage-configuration flammability of materials that fail Test 1 but are to be isolated in sealed or vented containers.

In the past 20 years, NASA material organizations have compiled a database of nearly 8000 materials tested in air or enriched-oxygen atmospheres. It is recognized that many essential materials do not "pass" these tests; their acceptability is verified in their locations or end-use configurations by waiver, analysis, or additional testing (ref. 20). Prior to each Shuttle mission, the on-board locations of materials and items are mapped, and possible fire-propagation paths are evaluated for control. Photographs of the spacecraft interior are made for reference.

Atmospheric controls.—For life support, the first U.S. human-crew missions (Mercury, Gemini, Apollo) had 100 percent-O_2 atmospheres and a reduced pressure of 34.5 kPa to keep the pressure differential across the lightweight spacecraft structure low (ref. 21). The present Shuttle orbiter structure permits a sea-level-equivalent pressure of 101.3 kPa, with a composition of 21 vol % O_2 in nitrogen (air). The Shuttle space suit used for extravehicular activities (EVA), however, has a breathing atmosphere of 100 percent O_2 at 30 kPa pressure to permit flexible glove operation. To avoid decompression sickness from the sudden decrease in atmospheric pressure, the crew members must be conditioned to remove nitrogen from their blood stream prior to the EVA. This is accomplished by prebreathing 100 percent O_2 for 4 hr. Alternatively, the cabin total pressure may be reduced to 70 kPa by removal of part of the atmospheric nitrogen for at least 12 hr. (This raises the oxygen concentration to 30 percent.) Only 40 min of crew oxygen prebreathing prior to an EVA is required with the reduced-pressure Shuttle atmosphere.

It is interesting to note that some atmospheres that support human life may not support fire spread (ref. 22). For example, a breathable atmosphere with a near-sea-level quantity of oxygen (a partial pressure of 21 kPa) but a low percentage of oxygen inhibits fire growth because of the cooling or quenching effects of the excess atmospheric diluent. In submarines, this principle is the basis for fire control by nitrogen flooding to dilute the oxygen concentration in the existing air atmosphere (ref. 23). Unfortunately, since nitrogen flooding substantially increases the atmospheric pressure, the method is unsuitable for use in a limited-strength spacecraft structure.

Humans can also tolerate long-duration exposures to atmospheres with oxygen partial pressures of 80 percent or less of the sea-level equivalent, corresponding to high-altitude conditions (ref. 24). These reduced-oxygen atmospheres, which inhibit fire spread, may also have medical advantages in improving the acclimatization of humans to low gravity and stress conditions (ref. 25). On the other hand, these altered atmospheres could have detrimental effects on human efficiency and performance under the long-term, rigorous conditions of space station missions. In any event, the adoption of a low-oxygen atmosphere for the first generation of *Freedom* is unlikely, because, among other reasons, it may compromise or confuse life-science and materials experiments that require "air" atmospheres for reference conditions. Moreover, lower-oxygen atmospheres may not be completely fire-free, since some potential space hazards such as smoldering may yet occur under these conditions.

Problems in spacecraft fire prevention.—There are at least three deficiencies in the present fire-prevention practices for spacecraft that must be recognized and eventually addressed. These shortcomings are in the nonconformity of the present acceptance tests to research and industry standards, the necessity to accept obviously flammable materials on spacecraft, and the absence of low-gravity correlations to predict material performance under actual space conditions.

The NASA NHB 8060.1C Upward Flame Propagation (Test 1) is a screening test, designed to evaluate materials under worst-case atmospheres, usage thicknesses, and flame-propagation conditions. Flammability assessments of the NHB 8060.1C test cannot be correlated with industry and aircraft standards for peak and total heat release (ref. 26). While there may be no particular advantage in having common flammability criteria among space, aircraft, and other transportation sectors, heat-release and flame-spread-rate standards may be applied to the prediction of flammability based on material properties. The cited study of Ohlemiller and Villa (ref. 26) also noted that preheating the samples prior to ignition in the NASA test may be more representative of potential in-space ignition scenarios.

Articles carried on spacecraft include a number of materials and components, with no effective substitutes, that could not qualify as nonflammable by any criterion. These items include paper, film, cotton clothing and toweling, some foam padding, Velcro® patches, and many commercial instruments and components. The Shuttle control system, already noted, inventories these articles, identifies the hazards, and prescribes the proper storage or protection. For the long-term missions of *Freedom*, however, more flammable materials may be present, protective configurations may change with time, exposure to ignition sources may increase, and attention to proper handling of flammable materials may decay with overconfidence.

Finally, as additional low-gravity data are generated, the application of normal-gravity tests and standards to predict low-gravity flammability should be re-evaluated. As a practical matter, the testing of spacecraft fire-safety technology, including fire detection and intervention equipment as well as material-flammability screening, must be performed on Earth where, in contrast to the use environment, buoyant motion dominates. For many years, normal-gravity flammability assessments were accepted as representative of worst-case situations; that is, materials could be considered more flammable on Earth than in space. This assurance is based on the results of the in-space experiment on Skylab in 1974 (ref. 15), where Kimzey demonstrated that, in all cases, the flame-spread rate of materials was less in low gravity than in normal gravity. Similar experiments in free-fall drop towers on liquid pool fires (ref. 13) and on fires spreading along thin paper fuels (ref. 27) came to the same conclusion, provided that the measurements are made in a quiescent atmosphere. Comparisons of relative flammability at low and normal gravity must recognize that test conditions are not directly comparable except at very high forced-flow rates. While it is possible to have a truly quiescent microgravity surface-burning experiment, this is not the case in normal gravity, owing to the buoyant convection caused by the flame. In fact, an important finding of the microgravity flame studies is that the addition of small forced flows (typical of spacecraft ventilation) broadens low-gravity flammability limits and increases flame-spread rates. These conclusions are based on studies with forced flow opposed to the flame spread, analogous to the downward burning case in normal gravity (refs. 14 and 27). Initial results of the opposite, wind-aided or upward burning, flow case have been reported (ref. 28), but comparative data on low- to normal-gravity flammability limits and flame-spread rates are not yet available.

Recently, T'ien (ref. 29) has reported the results of analyses of flammability limits of plausible, hypothetical materials as functions of atmospheric oxygen fractions. Because of the crossing of the flammability boundaries, the model showed it is possible that the comparative flammability ranking of two materials in low gravity could be the reverse of their ranking in normal gravity.

There are other unusual combustion-related phenomena in microgravity that may influence the assessment of material flammability. For example, the NHB 8060.1C Test 1 will reject materials that drip hot particles to ignite a paper sheet below the test specimen. Small-scale experiments have shown, however, that in low gravity there is a radial expulsion of hot particles from some common materials with no preferred "drip" direction (ref. 30). Other phenomena of concern include the persistence of flammable aerosols or particle clouds in low gravity (ref. 1) and the greater likelihood of smoldering combustion that is difficult to recognize and control (ref. 31).

Fire Detection

Current practices.—Fire-safety strategies must always assume the probability of a breakdown in fire prevention, and thus provisions for early-warning fire detection in spacecraft are essential. In the early U.S. spacecraft, the senses of the crew functioned as fire detectors. As missions became too complex to rely solely on human observations, automated fire detectors were installed in the spacecraft, starting with the Apollo project. The range of sensors investigated for space applications included ultraviolet flame detectors, chemical-specie detectors, condensation-nuclei smoke detectors, and quartz-crystal microbalance smoke detectors (ref. 5).

At present, the pressurized Shuttle Orbiter cabin space is monitored by nine ionization smoke detectors. If the payload bay is used for a human-crew laboratory (Spacelab or Microgravity Lab), it also has smoke detectors. The Shuttle detector is identical in concept to ionization smoke detectors in common usage in buildings and aircraft. It has two ionization chambers, a sensing and a reference chamber, to reduce its sensitivity to changes in pressure or humidity. An integral fan creates an internal flow at the angled entrance tube to the chambers, bypassing high-momentum particles (probably those nominally greater than 5 μm in size), likely to be dust rather than smoke. The fan flow also guarantees adequate sampling in the absence of natural-convection flow in low gravity. Internal logic circuits require the buildup of particles for a predetermined time prior to actuation, to reduce false alarms. Alarm levels are set for a particle density of 2 mg/m^3 sustained for 5 s or for a rate of rise of 22 μg/(m^3)(s) for 20 s. Thomas (ref. 32) estimated that the smoke density at the set point is a factor of five lower than that of a visible smoke column (in normal gravity). In the three Shuttle incidents of component overheating and short circuits, the crew observed the smoke emissions and took action to deenergize the affected circuits before the smoke alarm actuation levels were exceeded.

Future trends.—The Space Station *Freedom* will be an assembly of occupied cylindrical chambers, called modules, interconnected by smaller nodes (fig. 5). Within each module, and on a smaller scale within each node, there are four longitudinal banks of equipment racks enclosing the central core, or working corridor. Fire-detection proposals for *Freedom* call for smoke detectors as the primary protection and radiation flame detectors as supplements. Figure 6, to be discussed later as an example of fire-extinguishment provisions, shows the location of a smoke-detection station in the ventilating-air return plenum in a rack. Similar installations are planned for the protection of the central core and other inhabited volumes of the *Freedom* complex.

A conceptual design of a proposed *Freedom* smoke detector is shown in figure 7. The smoke detectors use the principle of photoelectric light scattering, with dual beams to respond to both light scattering (indirect beam) and light obscuration (direct beam). The two beam sensors complement one another for detection and reference. Proposed detection-alarm levels for *Freedom* are based on light attenuation equivalent to a 5.3x10^{10} particle/m^3 smoke concentration and a 1.6 percent/m optical smoke obscuration. These criteria differ from those of the Shuttle, which are based on particle mass concentration (2 mg/m^3, as noted previously). The comparative sensitivities of the present and proposed alarm levels depend on assumptions of typical particle mass and size, factors that have been discussed in the literature (refs. 32 and 33). The selection of photoelectric smoke detector for the *Freedom* proposal, instead of the ionization smoke detectors used currently in the Shuttle, is based in part on an earlier tradeoff study (Opfell, unpublished report). A recent review notes that the advantages of photoelectric smoke detectors are the insensitivity to particle size (possible better response to smoldering), insensitivity to environmental changes, and simpler construction (ref. 33).

Supplementary flame detectors in *Freedom* will protect the module central cores and other high-risk spaces, such as galleys. Figure 8 shows a conceptual design of a radiation detector tuned to three bands in the ultraviolet, visible, and infrared wavelengths, selected to combine high sensitivity to fire-constituent radiation with strong false-alarm rejection. The sketch also shows an estimate of the line-of-sight coverage of the fixed-position detector. An investigation of the application of fiber optics to extend the viewing field of flame detectors and to improve the efficiency of detection with a limited number of sensors in spacecraft has been reported (ref. 34).

Atmospheric sampling is another means of fire detection, not yet exploited in spacecraft. *Freedom* will have provisions for continuous atmospheric monitoring incorporated in its environmental control and life support system (ECLSS). Continuous measurement of carbon monoxide trace constituents in the ECLSS monitoring can offer a sensitive means for detecting not only incipient fires but also emissions from nonflaming pyrolysis and smoldering (ref. 33).

<u>Problems.</u>—Fire "signatures" in low gravity often differ from those monitored in normal gravity. Initial research on stabilized microgravity gaseous diffusion flames show them to be sootier yet cooler than their normal-gravity counterparts (ref. 12). Otherwise, there are no quantitative data on the smoke characteristics of mean particle size, size distribution, and particle density of microgravity flames. A reasonable assumption is that microgravity fires generate smoke particles larger than those of normal-gravity fires because of particle agglomeration due to the absence of convective stirring. Thus, smoke detectors that reject larger particles as "false alarms" may be insensitive in low gravity.

Radiative emissions from low-gravity flames are also different from those of normal gravity. Recent studies of Bahadori, et al. (ref. 12), investigating the radiation from microgravity gaseous diffusion flames, showed that the total radiant energy is significantly higher in microgravity compared to normal gravity. On the other hand, studies of flames spreading across liquid or solid surfaces in a quiescent microgravity atmosphere (refs. 13 and 14) showed that the flames are dimmer and more blue than their normal-gravity counterparts (implying less radiation). Furthermore, small-scale experiments demonstrated that microgravity flames are steady and do not flicker (ref. 35), and thus conventional flame detectors with flicker circuits to filter out steady ambient-light interference may also reject low-gravity fire signatures.

In addition to the changes in signature qualities, system designs and detector placement in spacecraft must recognize that the heat and mass transport of gaseous and aerosol signatures is slow due to the near absence of natural convection. For *Freedom*, decisions are yet to be made on the optimum number and spacing of detectors, the system redundancy and multiple-space zoning, the tradeoffs of automation versus manual responses, and the sensitivity levels for warning and alarm for balance of safety against false-alarm rejection. System designs must also meet the rigorous limitations on mass, volume, and power.

Fire Extinguishment

Current status.—One of the authors has recently reviewed the status of spacecraft fire suppression and extinguishment (ref. 36). In the early U.S. human-crew spacecraft, the metering water dispenser was designed as an alternative fire extinguisher, although it is questionable whether this method could control any hazard beyond an incipient fire. In later missions, aircraft-type, aqueous-gel foam and halogenated hydrocarbon fire extinguishers were installed in the spacecraft (refs. 5 and 37).

At present, the Shuttle is equipped with three remotely actuated, fixed fire extinguishers and additional portable fire extinguishers, all charged with Halon 1301 (bromotrifluoromethane). The fixed extinguishers are mounted in the three electronic bays, and they are sized to discharge sufficient agent to achieve a local concentration of 6 to 7 percent in approximately 1 sec. An extinguisher has been discharged in space for demonstration but never for fire fighting. Shuttle mission rules call for an immediate termination of the mission and return to Earth following the discharge of a fire extinguisher.

Future trends.—Halon 1301 is among the halogenated compounds to be banned by international protocol in the coming decade, and eventually it may be unavailable for spacecraft usage. The proposed alternative is carbon dioxide as the agent for both fixed and portable fire extinguishers. A conceptual schematic of the CO_2 system for *Freedom* is shown in figure 9. A central supply, consisting of two redundant tanks in each U.S. module, is connected to a common manifold for each bank of racks. Within a typical rack, there will be a dry perforated pipe as a distributor for flooding suppression (fig. 6). The CO_2 release valves are remotely operated with manual overrides. Note that the fire detection and suppression panel on the front of the rack has a port for insertion of the nozzle of a portable fire extinguishment, if necessary.

Carbon dioxide as an extinguishing agent has recognized problems of inefficiency and toxicity in excessive concentrations (ref. 38). The selection of carbon dioxide as the agent for *Freedom* was based on a design tradeoff study (Opfell, unpublished). Subsequent independent system-analyses studies (refs. 39 and 40) have also given carbon dioxide the highest score among competing agents in response to typical spacecraft fire scenarios, although the superior ranking of carbon dioxide is based on subjective, marginal criteria. For the inhabited hyperbaric chamber in *Freedom*, a space reserved for medical treatments and decompression recovery after extravehicular activities, carbon dioxide is the proposed primary fire-extinguishing agent, but nitrogen flooding is being considered for supplementary, emergency extinguishment.

Freedom also has the capability of automatic venting of its atmosphere to the vacuum of space for fire control. Attempts to extinguish fires by withdrawing the spacecraft atmosphere cause internal flows and forced convection, which may temporarily intensify a fire (ref. 15). The residual total pressure sufficient for extinguishment, whether in normal or in low gravity, is not known. Available atmospheric-gas stores on *Freedom* are limited to slightly more than the quantity needed to support one complete venting and subsequent resupply. Obviously, venting may be considered as an alternative only as a last resort for an otherwise uncontrollable fire, after crew evacuation of a module.

Problems.—Reuther (ref. 40) suggested that there may be some chemical and physical differences in the reactions of extinguishing agents between normal- and low-gravity environments. A greater concern, however, is in the effectiveness of the physical dispersion and removal of extinguishing agents in low-gravity fires. In some of the Skylab microgravity combustion tests, Kimzey (ref. 15) directed water sprays at the burning fuel samples. The water spray broke up into discrete droplets, and they scattered some of the burning material before extinguishing the flame. These early results indicate how difficult it may be to control and distribute liquid and solid sprays in the microgravity environment. After extinguishment, the excess, unreacted liquid and solid agents can persist as polluting aerosols in the spacecraft atmosphere. Because of these formidable challenges of effective dispersion and subsequent cleanup of the spacecraft atmosphere and surfaces, only gaseous agents are serious contenders for use in spacecraft.

For the permanent missions of *Freedom*, there will be no option of the return of a module to Earth for conventional cleanup. Fire safety in *Freedom* must involve the complete cycle from detection to repair, all conducted using resources available in the station. Of particular concern are the subtle, long-term toxic and corrosive effects from the fire and extinguishment residues. This may be another strong reason to eliminate Halon 1301 in the near future, because its extinguishment action generates at least small quantities of HF and HBr. The closed-cycle atmospheric revitalization subsystem is an important component of the proposed *Freedom* environmental-control system. The subsystem is to have a trace contaminant control with an adsorbent bed to remove aerosols and a high-temperature catalytic oxidizer to convert carbon monoxide and other gaseous combustion products into carbon dioxide and water for subsequent removal and recycling (ref. 41). The trace contaminant control subsystem cannot be sized to handle the excess effluents from an established fire. A promising approach to emergency atmospheric control is through an auxiliary, high-response contaminant removal and recycling unit feasible for space operation. Conceptual designs of such a system has been described recently, with analyses of the response and cleanup times for a small and a large fire scenario (ref. 42).

Fire-Response Management

The total program of fire protection must also consider fire-control procedures that allow the automatic response to an alarm to be overridden manually, permitting this decision to be made by relatively untrained crew personnel. Figure 10, adapted from unpublished NASA Marshall Space Flight Center and Boeing Defense and Space Group documents, illustrates the schematic concept for responses to a fire alarm originating in an equipment rack. The data-management system is programmed to assess the detector signal to distinguish false alarms (perhaps through rate-of-change or verification programs) and then reset to normal conditions, if warranted. The subsequent automatic response to a verified alarm is a shutdown of the rack electrical power and ventilating-air flow, prior to carbon dioxide release. The crew may override the automatic agent release, with decisions available to take minimal shutdown action, release carbon dioxide manually, or other responses.

Fire hazards will also be present during the assembly period of *Freedom*, a process occupying a span of the order of five years. After the first year and a half of assembly, one or more of the pressurized modules will be in orbit and occupied periodically by a work crew. A fire-supporting atmosphere may be present even when the station is not occupied. (In 1973-1974 (ref. 21), the Skylab space station atmosphere was evacuated between attended periods.) Thus, an automated fire detection and suppression subsystem is essential for control of fire incidents occurring between occupied assembly periods. A reduced total pressure but enriched oxygen atmosphere, proposed for the assembly stages to assist the frequent exits and entrances for extravehicular activities, will increase the potential flammability of spacecraft materials. A review of contingency scenarios for the assembly (McDonnell Douglas, unpublished) has made recommendations for crew intervention, design, and process improvements to alleviate some of these hazards. Key suggestions include portable toxic-gas monitoring equipment for the assembly crew, manual depressurization and flow-shutoff valves outside of each module (but inside *Freedom*), and remotely operated hatches to allow module or node isolation through ground signals.

CONCLUDING REMARKS CONCERNING SPACECRAFT FIRE SAFETY RESEARCH NEEDS

Fire is a major catastrophic threat to spacecraft, and the space transportation sector has responded to date with specialized requirements based on limited experience and adaptations of fire-safety techniques from other sectors, particularly aircraft. For future long-duration and complex missions, fire-safety technology must be adapted to respond to the unique fire characteristics in the low-gravity spacecraft environment. Planning for adequate levels of safety in spacecraft requires not only an understanding of the low-gravity, fire-related behavior of materials and fire-safety devices but also the relationship between normal-gravity and low-gravity behavior.

There are several areas of investigation that need continued emphasis to apply microgravity combustion knowledge to spacecraft fire safety. More research is required to understand the atmospheric-dilution and oxygen partial-pressure dependence for ignition and subsequent flame spreading over solid materials, particularly for flow-assisted (flame propagating downstream) configurations, for which there are very few experimental data in microgravity. The extension of these studies to the comparison of low-gravity flammability, in all flow configurations, to normal-gravity flammability will allow the reinterpretation of normal-gravity material screening tests. To date, very few low-gravity experiments have been conducted with the engineering materials used in spacecraft. This is because most real engineering materials burn too slowly to be tested in drop towers (2 to 5 sec maximum microgravity time) or aircraft (about 20 sec of low gravity). Long-duration microgravity testing of these materials should be instituted, including tests on representative material geometries to allow study of flame propagation to adjacent surfaces. Smoldering combustion is also a serious concern for spacecraft, where foam insulation and waste storage provide archetypal sites for initiation of non-flaming combustion. Research results on microgravity smoldering are currently lacking because smolder propagation is so slow (approximately 0.5 mm/sec) that experiments cannot be conducted using ground-based low-gravity facilities.

Spacecraft fire detection is currently based on knowledge of the particulate and radiant emissions from normal-gravity fires. The actual emission characteristics of microgravity fires must be studied to allow more appropriate designs of spacecraft fire detectors. In addition, the effectiveness of the extinguishing agents under consideration, and their delivery and cleanup, must be studied in low gravity. This is particularly important for *Freedom*, where fire extinguishment systems may have to operate automatically in unoccupied modules.

In summary, progress in the understanding of the significant differences between low-gravity and normal-gravity combustion now offers the opportunity to improve fire-safety techniques through anticipation of and efficient responses to probable spacecraft fire situations. The principal challenge will be in the applications of fundamental microgravity science, advanced safety technology, and quantitative risk assessments into a practical policy of fire safety for the designs and operations of future spacecraft, particularly in the complex, permanent orbital operations of the Space Station *Freedom.*

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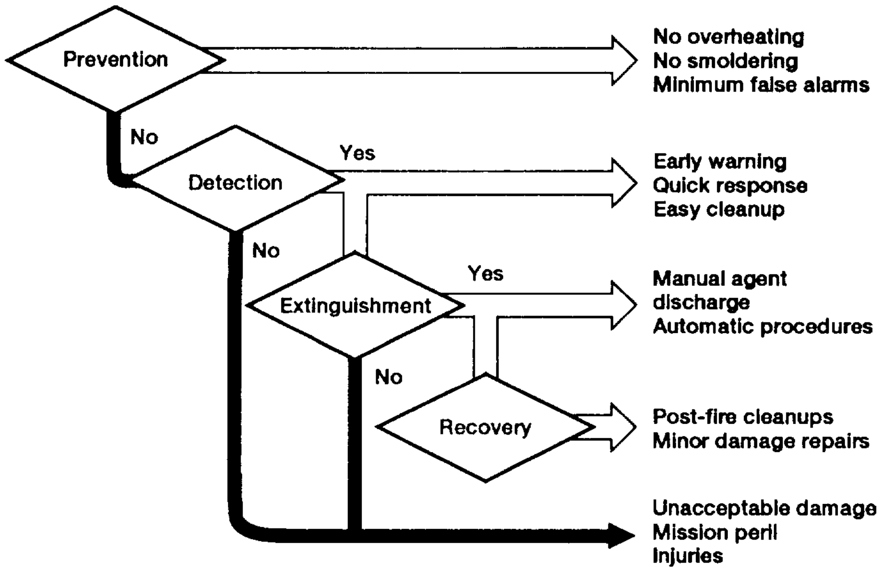

Figure 1.—Representation of the U. S. spacecraft fire-safety strategy.

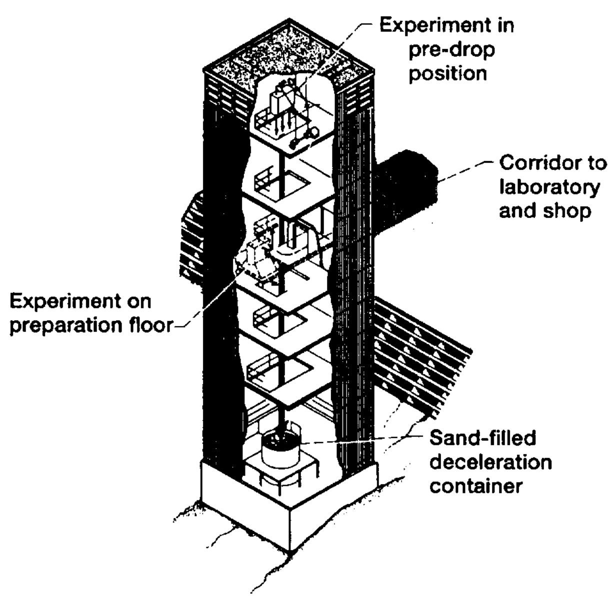

Figure 2.—NASA Lewis Research Center 27-meter drop tower
for microgravity research (low-gravity duration of 2.2 seconds).

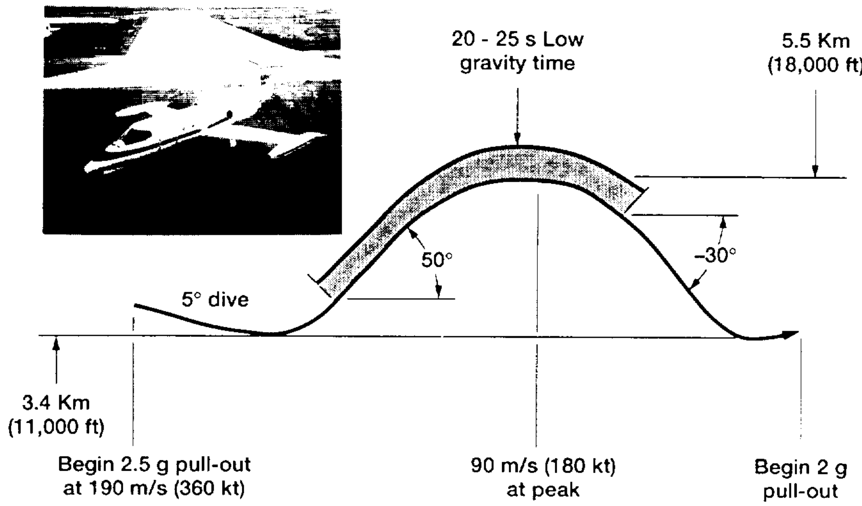

Figure 3.—Airborne laboratory managed by the NASA Lewis Research Center for reduced-gravity research.

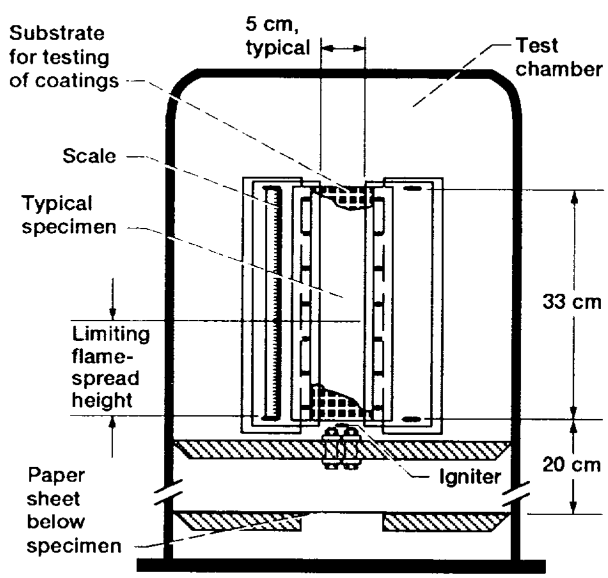

Figure 4.—Test apparatus for NASA NHB 8060.1C Test 1 for upward flammability.

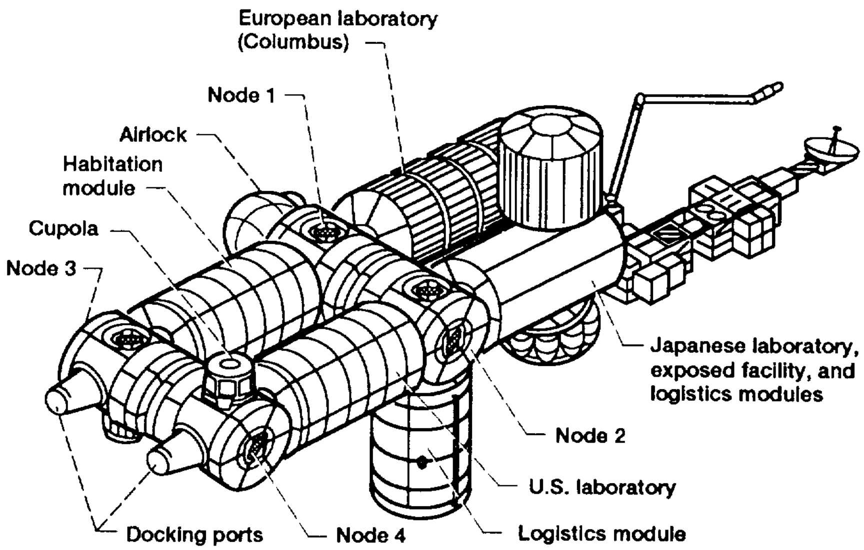

Figure 5.—Design concept of occupied volumes for the Space Station Freedom.

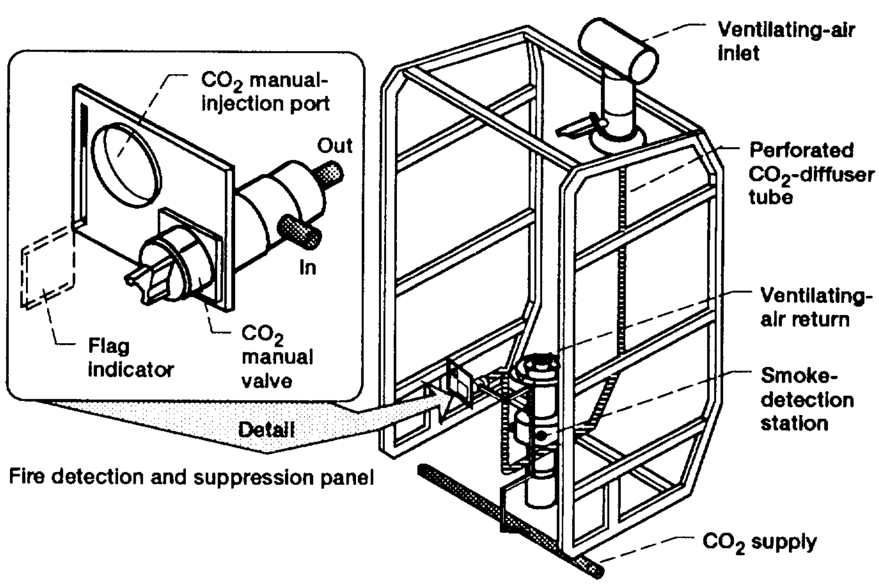

Figure 6.—Fire detection and suppression provisions in the design of typical Freedom equipment racks (courtesy of Boeing Defense and Space Group).

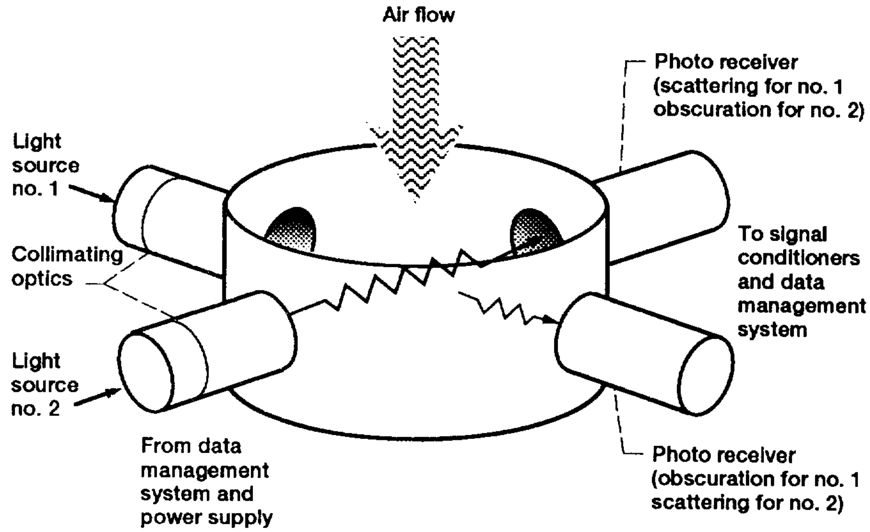

Figure 7.—Conceptual design of Freedom smoke detector station (courtesy of AiResearch Los Angeles Division).

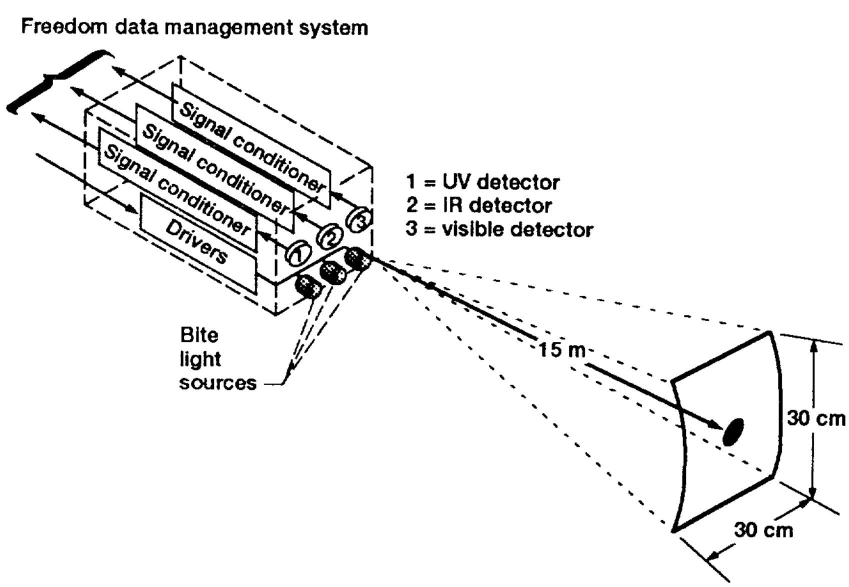

Figure 8.—Conceptual design of Freedom radiation flame detector (courtesy of AiResearch Los Angeles Division).

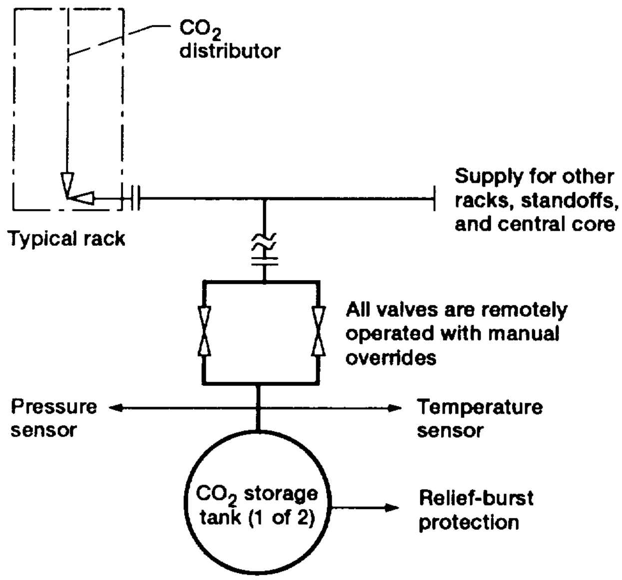

Figure 9.—Conceptual schematic of carbon dioxide fire-suppression system for Freedom

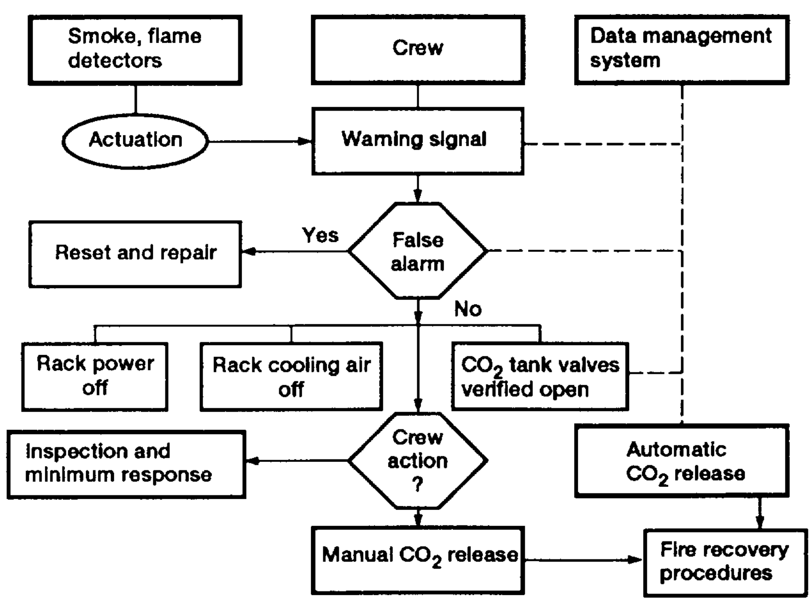

Figure 10.—Representation of fire-response logic for the Space Station Freedom

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13. ABSTRACT ***(Maximum 200 words)***
Current fire protection for spacecraft relies mainly on fire prevention through the use of nonflammable materials and strict storage controls of other materials. The Shuttle also has smoke detectors and fire extinguishers, using technology similar to aircraft practices. While experience has shown that the current fire protection is adequate, future improvements in fire-safety technology to meet the challenges of long-duration space missions, such as the Space Station Freedom, are essential. All spacecraft fire-protection systems, however, must deal with the unusual combustion characteristics and operational problems in the low-gravity environment. The paper discusses the features of low-gravity combustion that affect spacecraft fire safety, and the issues in fire protection for Freedom that must be addressed eventually to provide effective and conservative fire-protection systems.

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